Our heliosphere: The new view from Voyager

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Our Heliosphere: The New View from Voyager

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Abstract. Launched in 1977 on a journey to the giant outer planets and beyond, Voyager 1 and 2 have explored the spatial and dynamical properties of the heliosphere that modulates the inward flow of galactic cosmic rays and is the source of anomalous cosmic rays. The two spacecraft are in the heliosheath beyond the termination shock where the supersonic solar wind has slowed as it approaches the boundary of the heliosphere. The shock crossing was 10 AU closer at Voyager 2 in the south than at Voyager 1 in the north, indicating a local interstellar magnetic field pressing inward more strongly on the southern hemisphere. The expected source of anomalous cosmic rays was not observed at the shock, and their intensity has increased deeper in the heliosheath, indicating the source is elsewhere on the shock or in the heliosheath. Voyager 1, now at 121 AU at 35 degrees north, has been in a quasi-stagnation region since 2010 where there is no outward motion of the wind, the magnetic field is enhanced, and the galactic cosmic ray intensity is increasing. In contrast, the heliosheath flow at Voyager 2 at 99 AU and 30 degrees south is faster and increasingly deflected in a non-radial direction as it turns to flow tailward. These observations will be placed in the context of current models of the interaction of the solar and interstellar winds.

Keywords: Heliosphere, solar wind, Voyager 1 and 2, galactic cosmic rays, anomalous cosmic rays
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INTRODUCTION

The Voyager 1 was launched 35 years ago to Jupiter and Saturn on Sept. 5, 1977. Voyager 2 had been launched a few days earlier on Aug 20 and was to go past Uranus and Neptune as well. These spacecraft had instruments designed to measure the solar wind plasma, energetic particles and cosmic rays, magnetic fields, and plasma waves and kilohertz radio emissions [1].

The Voyagers completed their studies of the planets in the 1980s and have since been heading to the outer heliosphere in search of the boundaries of the regions where the heliospheric and interstellar plasmas interact. As early as 1955 Davis [2] postulated that solar corpuscular radiation would create a bubble in the surrounding interstellar matter. Parker [3] predicted that a stellar wind would create an astrosphere about the star and showed that an interstellar wind would create a comet-like astrosphere with its nose heading into the interstellar wind.

Figure 1 shows a view of how a bow shock might form upstream of a solar wind termination shock and where the two Voyager spacecraft are headed [4, 5]. Also shown is an image of the Orion Nebula from the HST where such a boundary region is seen in collisionally induced emissions from oxygen, nitrogen, and hydrogen.

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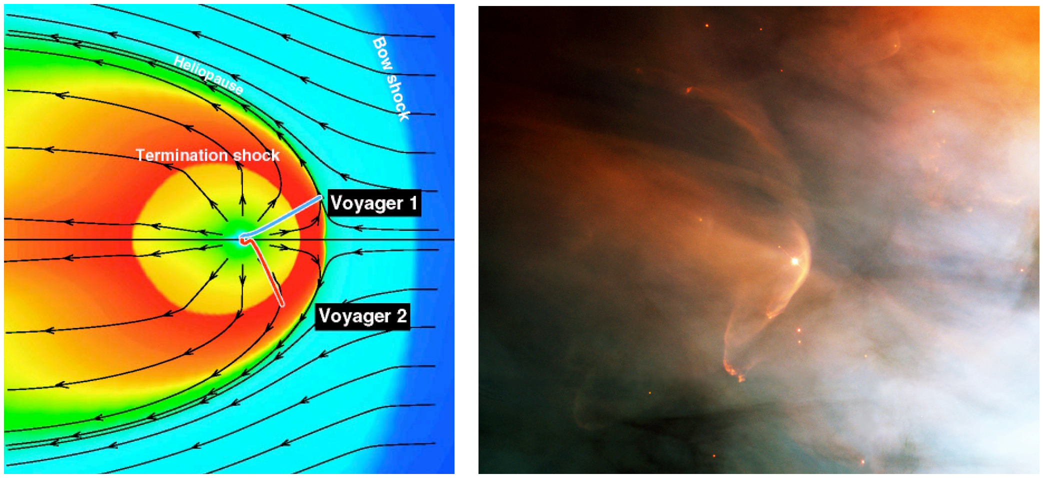

Figure 1: On the left is shown a model [4, see also 5] of the solar wind interacting with the interstellar wind. On the right is shown a bow shock created by the interaction of the wind from LL Ori colliding with the gas evaporating away from the center of the Orion nebula (credit NASA and the Hubble Heritage Team (STScI/AURA) and C.R. O'Dell, Vanderbilt University).

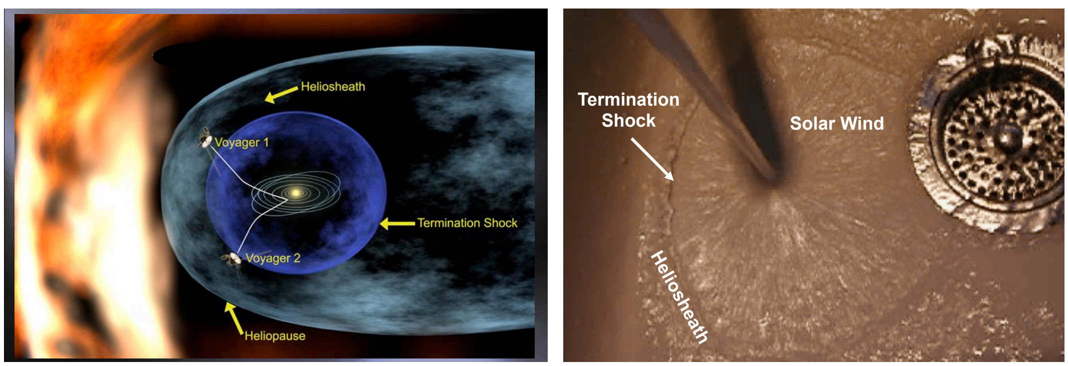

Figure 2: On the left is a simplified schematic of the heliosphere showing the termination shock where the supersonic solar wind abruptly slows, forming the heliosheath where the subsonic wind begins to turn to flow toward the heliospheric tail extending toward the right. On the right is a photograph of water flowing into a kitchen sink with the structures corresponding to those expected in the heliosphere.

A simplified drawing of the heliosphere is shown in Figure 2 for comparison with an analog of the heliosphere seen in a kitchen sink. The water hitting the sink bottom represents the sun and the fast radial flow corresponds to the supersonic solar wind, which abruptly slows in a shock and forms a thick ring (the heliosheath) where the water turns to flow down the drain.

TERMINATION SHOCK, NORTH/SOUTH ASYMMETRY

As can be seen in figure 1, Voyager 1 and 2 approach the heliospheric boundary from different directions, V1 going towards the north and V2 towards the south, allowing an exploration of the asymmetry of the system. As shown in figure 3,

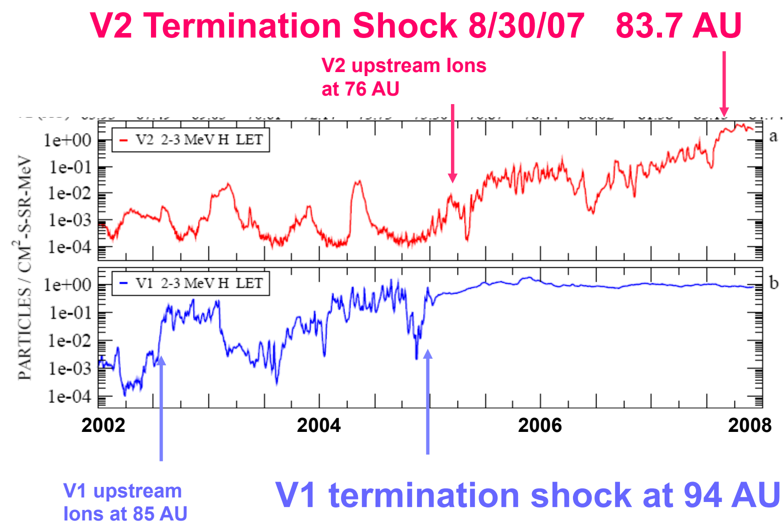

Figure 3: Intensity of 2-3 MeV H ions peaks at the crossings of the termination shock, indicating the shock is the source of low energy ions [6, 7]. These termination shock particle (TSPs) are convected into the heliosheath, filling it with a reasonably uniform intensity of TSPs.

V1 saw upstream ions at 85 AU and crossed the termination shock at 94 AU. At V2, these same crossings came closer to the sun (albeit later in time, due to the slower speed of V2). This north/south asymmetry is thought to be produced by the interstellar magnetic field pressing inward on the southern hemisphere. An initial model produced the asymmetry using a 1.8 microgauss interstellar field [8], but when the effects of neutral interstellar atoms are included, an interstellar magnetic field of 3 to 4 microgauss is required [9, 10, 11]. These analyses led to association of the local interstellar magnetic field with the shell of the Scorpius Centaurus superbubble [12].

TERMINATION SHOCK PARTICLES

The velocity of the wind dropped abruptly at the termination shock boundary, and thermal temperature of the plasma rose by about an order of magnitude as V2 entered the heliosheath region beyond the termination shock [13, 14]. However, only ~20% of the solar wind kinetic energy is found in the thermal plasma. The bulk of the energy was likely transferred to interstellar pickup ions [13] due to their efficient interaction with the shock [15].

As seen in Figure 3, the shock is the source of TSPs with energies mainly <10 MeV/nuc. The shock is a cosmic-ray mediated shock because the MeV TSPs propagate upstream of the shock, slowing the solar wind and reducing its dynamic pressure by 13% prior to the formation of the shock [16].

ANOMALOUS COSMIC RAYS

The expected Anomalous Cosmic Rays (ACR) spectrum at E>10 MeV/nucleon was not observed at the V1 or V2 shock crossings, indicating that the ACR source is elsewhere at the shock or further out in the heliosheath. The ACR intensity increased with increasing distance in the heliosheath until 2010 when V1 was >20 AU beyond the shock, then decreased slowly. The galactic cosmic rays continued to increase, suggesting that the ACRs might be leaking out through the nearby heliopause. However, the ACR decreases did not show the energy dependence expected from diffusive loss through a boundary.

Several new ideas have been put forth as possible sources for the ACRs. They could be accelerated at the flanks, the tail, or other hotspots on the termination shock [17, 18, 19]. Other proposed sources include compressive acceleration near the heliopause due to increased turbulence [20], reconnection in the heliosheath and at the heliopause [21], adiabatic heating and/or stochastic acceleration in the heliosheath [22], and a focused acceleration in non-uniform magnetic fields [23]. Further observations and analyses may help determine the location and process responsible for ACR acceleration.

HELIOSHEATH QUASI-STAGNATION REGION

After passing through the termination shock, the Voyagers entered the heliosheath. TSP intensities in the heliosheath were steady from 2007 until 2010, when they began to decrease to only half their intensity by mid-2012 This suggests that in this region (>113 AU) the pressure of suprathermal pickup ions at lower energies may be only ~50% of that seen during the previous 4 years since the crossing of the termination shock.

The region beyond 113 AU appears to be a quasi-stagnation region with the radial plasma speed $V_R \leq 0$ km/s, as determined by observations of the Compton-Getting anisotropy of 35 keV ions [24]. Although it was expected that the decrease of the outward flow speed resulted from the northward deflection of the plasma as it turned tailward, it was found instead that all velocity components had decreased and the spacecraft was in a quasi-stagnation region from 113 AU outwards [25, 26]. The characteristics of the quasi-stagnation region are summarized as follows:

- Wind at V1 slowed to V_R ~0 at 113AU
- $V_R \leq 0$ out to >120 AU
- V_T and V_N also decreased
- Magnetic field nearly doubled (~3x average pressure) [27]
- Direction (+T) indicates still in heliosheath [27]
- Quasi-stagnation can be produced by solar wind dynamic pressure changes with solar cycle or pressure transients like those created by merged interaction regions [28]
- If scale of the quasi-stagnation region is 15-20 AU, it will take another 2 to 4 years to reach the heliopause

GALACTIC COSMIC RAYS

In the heliosheath, TSPs and ACRs dominate the galactic cosmic rays (GCRs) by orders of magnitude. However, outside the heliosheath, the GCR intensity should increase, while TSPs and ACRs should be much lower. Since the crossing of the termination shock V1 has seen the intensity of cosmic ray ions steadily increase: H ions (150-380 MeV/nuc) at 6.8%/year, He (175-345 MeV) at 13.1%/year and electrons (7-14 MeV) at 62%/year (see paper by McDonald, these proceedings). The rate of >70MeV/nuc ions had been increasing at about 9%/year from 2009 through mid 2012, then on day 128 (May 7) of 2012 this rate started increasing more rapidly as shown in figure 3. The >70 MeV rate increased 5% increase in one week and 9% in one month. Similar percentage increases were observed for ions between 70 and 200 MeV and for ions > 200 MeV. The increased GCR intensities and spectra became close to those predicted for the interstellar medium by Webber and Higbie [29].

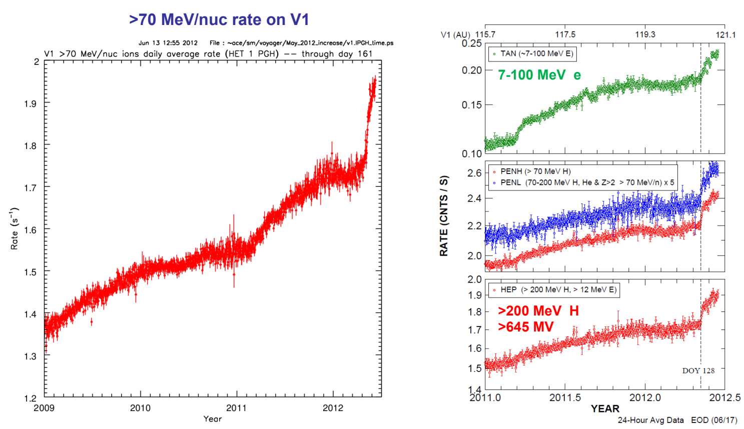

Figure 4: Evidence for a change in environment at Voyager 1 starting on day 128 (May 7). (Left) Daily average rate of >70 MeV ions at Voyager 1 since 2009. (Right) From top to bottom: green, 7-100 MeV electrons; blue, 70-200 MeV/nuc H, He and Z>2; red >70 MeV H; bottom red, >200 MeV H (>645 MV).

Other estimates have been made of the expected cosmic ray spectrum in interstellar space outside the heliospheric modulation region [30] and re-acceleration may play a role [31]. The estimates vary considerably in the energy range below 1 GeV. The predicted cosmic ray spectrum [31] of H in the local interstellar medium is 3 to 6 times the spectrum at 121 AU. It is of great interest to determine the intensity of particles in this low energy range as they are key to understanding the role cosmic rays play in heating the interstellar medium by ionization losses.

Further evidence that a new environment has been reached is that the intensity of 7-100 MeV electrons that have very low rigidities increased 20% since May 7. Similar, but smaller increases have occurred previously. This increase appears to be continuing with a simultaneous increase occurring over a rigidity range from >7 MV to >645MV.

In summary, after May 7, 2012 (day 128 of 2012) GCR ions > 70 MeV and >200 MeV increased faster than previously observed. The H and He spectra became similar to the Webber and Higbie estimate [29] of the interstellar spectrum, but still below that of Fisk & Gloeckler [30] and Moskalenko et al. [31]. 7-100 MeV electrons increased rapidly while ACRs decreased at lower energies. Have we entered a new distinct region? Are we observing some kind of transient phenomenon?

Voyager 1 is currently at 121 AU and is moving away from the sun at 3.6 AU per year. Is the heliopause nearby, several months or several years away? All the

Voyager instruments will have power to operate until 2020, but we expect them all to be off by 2025. Let's hope we reach the interstellar medium within a few years.

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